**International Journal of Engineering and Information Systems (IJEAIS)**
**ISSN: 2643-640X**
**Vol. 5 Issue 3, March - 2021, Pages: 127-136**

# Conceptual Modeling on Photon Detection Efficiency with Silicon Photomultiplier Calculator at Constant and Standard Variable Conditions.

**Sherice Malagon-King[1]*, Olabimtan Olabode. H[2] & Benjamin Abu. E[3]**

[1]Vent-r LLC, 10888 Buddy Ellis Road 45, Denham Springs, Louisiana, 70726, United State of America.
[2]National Research Institute for Chemical Technology, Department of Industrial and Environmental Pollution, Zaria Kaduna State, Nigeria.
[3]University of Jos, Faculty of Natural Science, Department of Chemistry, Jos Plateau State, Nigeria.
***Correspondent e-mail:Sherice@vent-r.com***

***Abstract:*** *Silicon based photomultipliers (SiPMs) have been a promising choice to vacuum photomultiplier tubes in terms of performance. A completely advanced execution of the Silicon Photomultiplier has been developed to overcome the shortcomings and constraints of the simple analog SiPMs (aSiPMs) in the discovery and identification of photons. A typical SiPM sensor depends on varieties of single-photon torrential slide photodiodes under standard conditions. Photons are recognized directly by detecting the voltage (over-voltage) at the anode of the single-photon torrential diode configured with cell hardware. This squared portion of the device additionally contains dynamic extinguishing and re-energizes circuits as the slightest bit of memory for the specific selectivity by the cells. A decent trigger mechanism is utilized to spread the signals from all the cells to the advanced incorporated converter. Eventually, photons are recognized and considered via some computerized signals with zero sensitivity to temperature, electronic noise, low consumption of power, and conceivable reconciliation of information with the sensor. Here, the detection capacities of SiPMs with a web-based simulator that incorporates the algorithms of the SiPMs performance were linearly modeled with the variable effects of the over-voltage supply. Certain constant conditions such as the electron multiplication gain ($10^6$), maximum after pulsing probability (30%), maximum UV- wavelength (905nm) with variable parameters as the voltage/over-voltage supply (20 to 100%) and the device responsivity (10 to 100) were adopted in achieving the maximum PDE of ($8.7820 \times 10^{-3}$) % and a minimum of ($5.269 \times 10^{-4}$) %.*

**Keywords:** Silicon photomultiplier, photon detection efficiency, over-voltage, responsivity and modeling.

## 1.0 INTRODUCTION

Silicon-based photomultiplier (SiPM) is also the solidified state photomultiplier detecting device with thousands of coordinated single-photon torrential slide microcells diodes pixels [1], [2]. In simplified SiPMs, cells are free and associated with a typical general readout with every cell having its extinguishing resistor with every microcell is squared with an edge length between 10 µm and 100 µm [3]. Upon the recognition of microcells, huge electrical signals will be induced with torrential slide augmentation. it is practically feasible to include each terminated and integrated SPAD( single-photon avalanche diodes) independently in a computerized system as advanced SiPM is associated with its readout hardware or by the abundance or charge of the amount of an average photon diodes signals with simple SiPM [4]. In any case, the SiPM permits one to identify and tally photons with high energy and with single-photon affectability as the interior driving slide enhancement is likewise swift enough to acquire excellent data of the recognized photons within picoseconds [5]. The silicon photomultiplier is a novel photon indicator idea dependent on torrential slide photodiodes running in Geiger form [6].

In numerous utilizations of SiPMs, one has to know irrefutably the number of photons that were episode on the SiPM as a flat-out alignment of the SiPM is vital. The general change factor from photons to the number of discernible photoelectrons is called photon detection effectiveness (PDE) and the successful quantum proficiency on account of vacuum photomultiplier [7]. The advancement with the edge identification structures for the low photon with silicon was initiated toward the start of the '90s from investigations of Silicon Metal Oxide Semiconductor (MOS) structures with torrential slide breakdown mode activity for identification of single light photon [8]. The outcomes were positive, however, a major impediment was the need to incorporate outer re-energize circuits for the subsequent charging of the MOS structure during the photons recognition. Hence, the subsequent stage was the execution of a unique resistive layer rather than oxide layers with Metal Resistive Semiconductor (MRS) structures, which re-energize the device after photon identification controlling the breakdown measure by extinguishing. Such constructions had exceptionally high and stable intensification attributes for photons recognition. The possibility of photomultiplier with silicon or Photoelectron Multipliers was made for conquering issue of previously mentioned structures as little delicate zone because of non-stability of enhancement over a huge territory, low distribution of power, and improved performance [8]. It was chosen to make the fine metal resistor semiconductor structure with nearby space dispersed pn-intersections miniature cells with normal yield. The outcome was

**International Journal of Engineering and Information Systems (IJEAIS)**
**ISSN: 2643-640X**
**Vol. 5 Issue 3, March - 2021, Pages: 127-136**

captivated as clear single-photon spectra were identified on the semiconductor structure at room temperature and were introduced at the ninth European semiconductor meeting in 1995[8]. As of late, Silicon Photomultipliers acquired interest as a likely contender to displace photomultiplier tubes (PMT) in a few applications for reasons of roughness, smallness, passiveness toward attractive fields, moderately low working voltage, low force utilization, and enormous scope creation prospects [9]. Today, silicon photomultipliers solely work in a simple route as the inactively extinguished Geiger-mode cells of the SiPM are equally associated through long interconnection and subsequent yield signal s with the microcells [9]. Therefore, the great characteristic exhibition of integrated single-photon diodes is not completely explored, as the induced signal is crumbled by the freeloading capacitances of the neighboring chips, the bond wires, and the external load [9]. From the device viewpoint, the huge scope of uses of simple silicon photomultipliers infers some difficulties involving a huge number of channels, where the devoted readout chips are expected to condition and digitize the SiPM signals. As the single-photon reaction is as yet in the mV range, the signs can be effortlessly influenced by electronic commotion or precarious pattern accordingly making single photon discovery troublesome [9]. A normal single-channel readout framework for the location of sparkle light dependent on the simple silicon-based photomultiplier (SiPM) is shown in fig. 1 below

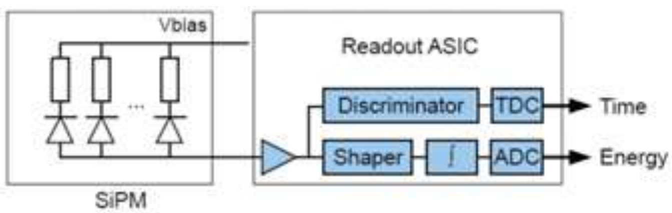



Figure 1a: Simple (Analog) silicon photomultiplier

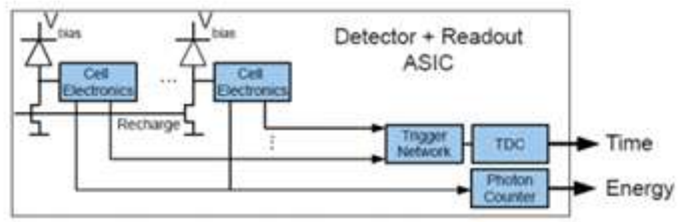



Figure 1b: Digitalized silicon Photomultiplier

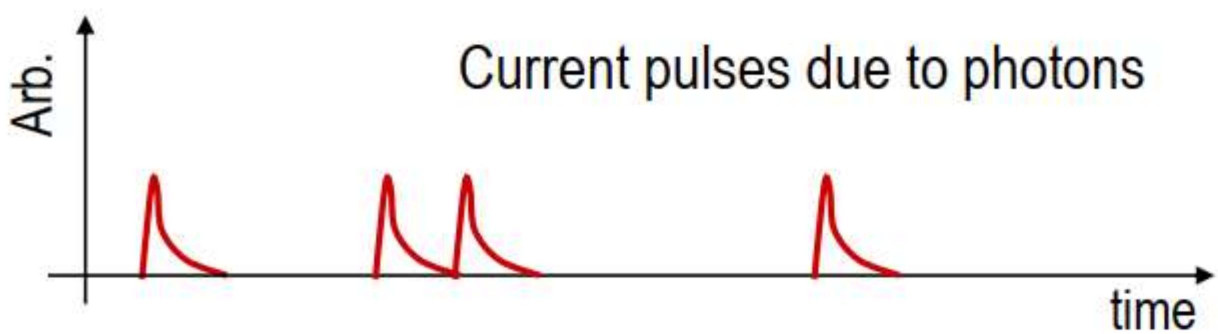



Figure 1c. The output of a SiPM as a chronological superposition of current pulses

The fundamental issue of the location of low photon motion or single photon is characterized by the idea of photons, material science of the photon cooperation, and cycles of changing the aftereffects of communication over to the electric sign, which is the changing component over the energy of photons to the electric signs [9]. The essential rule with the silicon-photomultiplier photon structure depends on the quantum of light photon transition as space conveyed quanta motion and space circulated cluster of miniature sensors with the capacity to distinguish single quanta of the light photon by each micro sensor. The principle of physical science cycle with photons communicate with the energy of photons over to the next structure as the photoelectric impact for the obvious scope of light [9]. For considering the nature of light and semiconductor material, this cycle gives the changing proportion of one to one photon energy making one electron-opening pair as this measure of electric charge is moved with estimation by an electronic framework [9]. The fundamental guideline of the photon distinguishing structure base on semiconductor materials micro sensor, which permits the aftereffect of photoelectric association, makes the semiconductor structure the chance of making a liberated district from charge transporters and the technique for transportation [10]. Silicon photomultiplier is a microstructure comprises of enormous quantities of rudimentary sensor varieties of miniature cells with torrential slide breakdown mode, space conveyed with the high thickness on the basic substrate, regular size of mm2, and associated individual miniature cells [11]. The detection efficiency by the silicon-photomultiplier is a result of not many primary components as quantum effectiveness, the proficiency of the torrential slide measure, and mathematical productivity. The quantum effectiveness of silicon photomultiplier is the broadest steady concept with the overall meaning of the quantum productivity of semiconductor identifying structures or devices. Photons enlightened the silicon-photomultiplier detectors by the energy over the band gap are consumed by the silicon precious stone design of the drained region and made the pair of the opening electron which can be identified by the signal. In certain distributions, the quantum productivity of semiconductor finders is characterized as variously estimated electrons at the yield of locator constructions to the information activity. However, on account of photomultipliers, the quantum effect is the proportion of made electron-opening sets to the approaching photon motion [8]. In genuine distinguishing structures as silicon photomultiplier, some portion of the photon motion is influenced by the reflection on the boundary of the touchy zone of the location structure. For the silicon, the reflection record on the line air-semiconductor is approximately 3.5 with the frenell coefficient for the ordinary occurrence photons R=0.3 which is the limitation on the reflection could reach ~30% [12]. This shortcoming could be productively diminished by the execution of the counter reflection jacket and will be restored for the quantum effectiveness of silicon photomultipliers. The primary factor which characterizes the quantum productivity is the qualities of the interaction of photons in the drained region of identifying structure. The photons impacting the silicon film cover some distance before transforming their energy to make a photoelectron. This distance is a component of the assimilation coefficient, which is characterized as the converse of the distance a photon transition goes in a material before being affected by an electron which is a significant boundary for the advancement on the silicon-photomultiplier as the thickness of the consumption layer is moderately slim [13]. Another part of this thought is that optical retention coefficients is a solid capacity of frequency as the energy of photons for the specific semiconductor material, and characterized the affectability reliance of quantum effectiveness to the frequency of distinguishing photons [14]. Cut off at long frequencies is a key constraint and happens for a silicon photodiode at a frequency of 1.1 μm where the photon energy is only adequate to move an electron across the silicon band gap. As this frequency is moved, the likelihood of photon assimilation diminishes quickly with expanding frequency. It will be noticed that the retention coefficient increments with expanding temperature will prompt an increment in long-frequency responsivity with temperature [15]. Cut off at low frequency happens with silicon-photomultiplier through the structural highlight of miniature-cells. The upper region of miniature cells is framed by the attachments of dispersion measure that characterizes the boundary of the exhaustion layer.

Photons consumed in this layer will not add to the charge collection cycle and this impact causes a solid decrease of the affectability of photodiodes for photons with a short frequency that is ingested near the surface [16]. The likelihood that the interaction of ionizations keeps on expanding until the entire pn-intersection is released is known as the avalanche breakdown probability [17].

The investigation of silicon photomultiplier detection performance shows that the torrential slide in the silicon photomultiplier structures is essentially higher [18]. The mathematical filling factor is the extent of surface region equipped for distinguishing single photons to the all-out region of silicon photomultiplier including mechanical boundary with some influencing factor on the filling factor is optic crosstalk, which is the capacity of the space amongst the miniature cells [19].

## 1.1 POTENTIAL UTILIZATIONS OF SIPMS

### 1.1.1 **Beam detection and ranging systems (LiDAR).**

One of the principle quality variables of present-day LiDAR frameworks in the auto business is the distance at which objects with a low reflectivity can be recognized. At present, the objective is to identify an item with 10% reflectivity a good way off of 300 m. To accomplish this objective, the silicon photo-multiplier (SiPM) is a required choice of the detector [20].

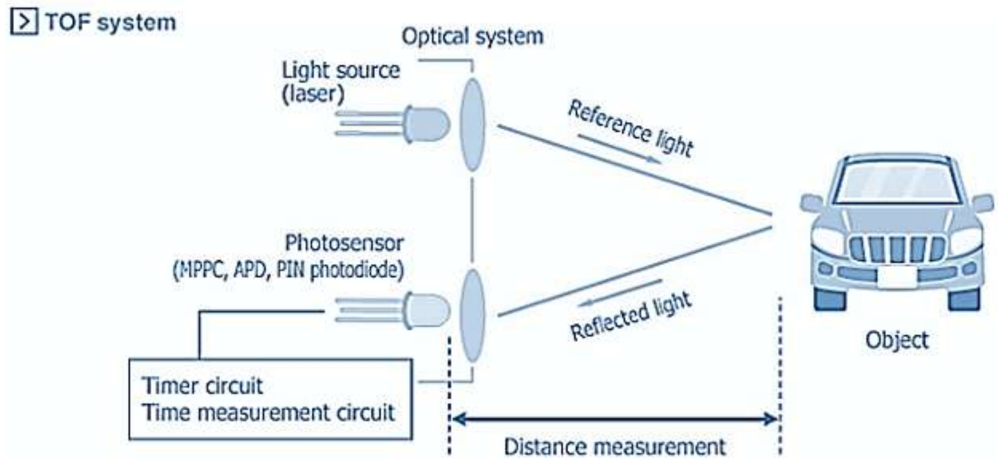



Fig 2: The LIDAR framework utilizes the hour of flight an impression of the light pillar (beat or persistent) to detect the environmental factors. (Picture: Hamamatsu Photonics K.K).

### 1.1.2 Flow cytometry

Photomultiplier cavities adopt anodes and cathodes devices in a cryogenic vacuum cylinder to produce photo-current through the light produced by the stream cytometry. The photon produced by the excitation of the fluorophore in the example, slams into a photocathode when entering the photomultiplier tube creating photoemission by electrons. The electrons produced by the photocathode move between the dynodes that are set falling down the photomultiplier tube. The development between the dynodes, which are additionally called anodes, brings about the age of optional electrons [21].

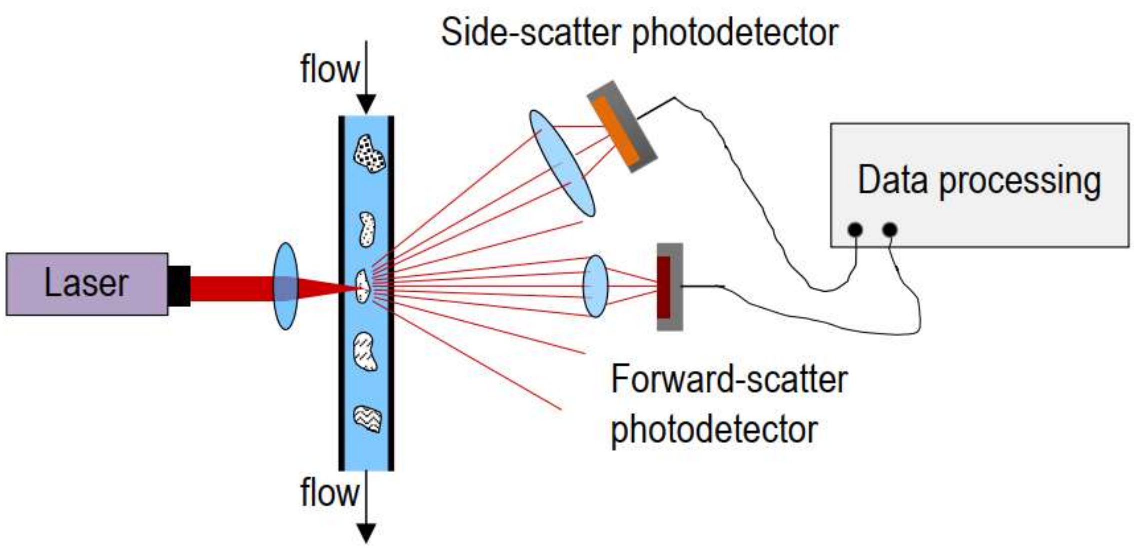



Figure 3. Flow cytometry

### 1.1.3 Radiation recognition and monitoring

Silicon photomultipliers offer an elective arrangement, consolidating a significant number of the upsides of photomultipliers cylinders and torrential slide photodiodes. They have high increase, incredible electro-physical properties, and are passive toward attractive fields. Right now, silicon photomultipliers innovation is quickly creating and in this manner, an examination concerning the ideal plan and working conditions is in progress along with a point-by-point portrayal of silicon photomultipliers - based positron discharge tomography identifiers. Distributed information is very encouraging and shows great energy and timing objective just as the capacity to disentangle little scintillator clusters. Silicon photomultipliers unmistakably can be the photo detector of decision for a few, or even maybe most, positron emission tomography [22].

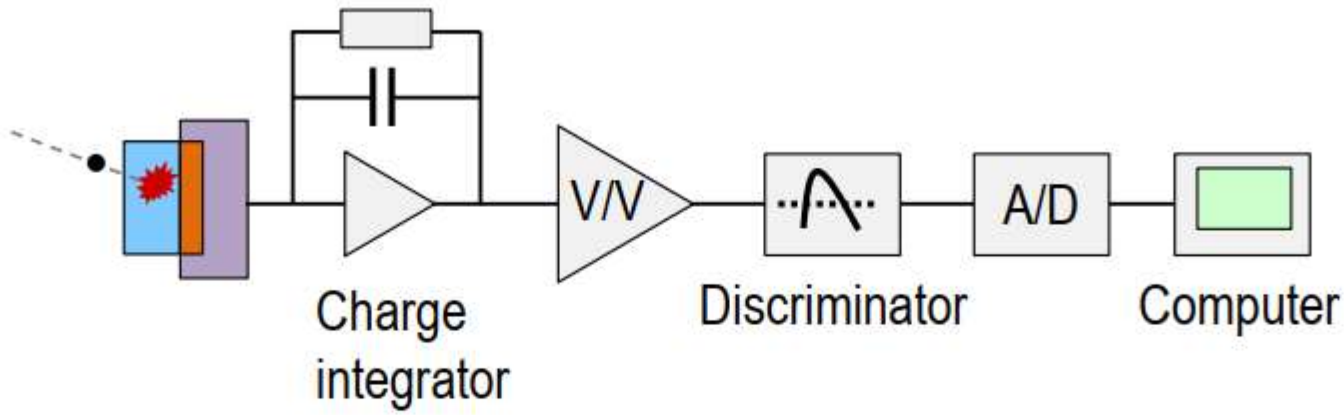



Figure 4. Radiation detection and monitoring pathway diagram

**2.0 METHODOLOGY**

To decide the photon detection proficiency of SiPMs, a regular technique in which an associated ultraviolet and monochromatic light source has to be contrasted along with the signal being forestalled. These are because of some natural highlights of the SiPM with the rate impacts, time management, and optical crosstalk. To precisely appraise the PDE, the commitments because of optical crosstalk with after pulsing should be considered as the previous occurs when a solitary episode of photon creates signals comparable to at least two photons and the last when a few transporters become caught within the silicon. After some time, up to a few nanoseconds, they are delivered, making an extra sign. The photon detection efficiency PDE was then basically assessed with the varieties of responsivity from 10 to 100 at the consistent estimations of gain multiplication of 106, greatest after the pulsing possibility of 30%, crosstalk possibility (over-voltage), and maximum UV wavelength of 905nm with a web-based calculator.

$$\mathbf{PDE} = \frac{\mathbf{Rhc}}{[\mathbf{e\lambda G\,(1 + P\_XT)\,(1 + P\_AP)}]}$$

Where:

PDE is the photon detection efficiency
R is the responsivity, which addresses radiant sensitivity of a photodiode or some other sort of photo detector with the proportion of generating photocurrent and occurrence of optical force in the linearity of the area of the detector. It is estimated in amps per Watt A/W

$h = 6.626 \times 10^{-34}$ m²*kg/s is Planck's constant
$c = 2.998 \times 10^{8}$ m/s is the speed of light
$e = 1.602 \times 10^{-19}$ C is elementary charge
$\lambda$ is the wavelength of the incident light
G is the gain (the amount of charge created for each detected photon)
P_XT is the crosstalk probability
P_AP is the after pulsing probability

Table 1. Typical specifications for a SiPM [23]

| Parameter | Value |
|---|---|
| **Gain** | 1,000,000 |
| **After pulsing probability** | 3-30% |
| **Applied voltage** | 20-100 volts |
| **Active area** | 36mm$^2$ |
| **Microcell size** | 5625 μm$^2$ |
| **Number of microcells** | 100-10,000 |
| **Received light wavelength** | 905nm |
| **High quantum efficiency** | 905nm |

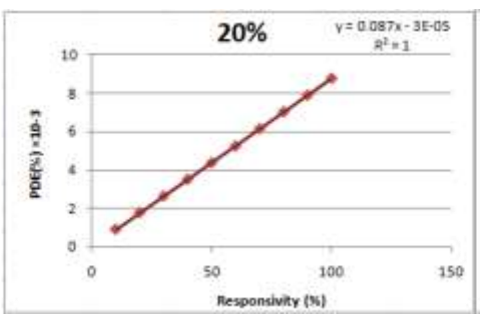
### 3.0 RESULTS AND DISCUSSION

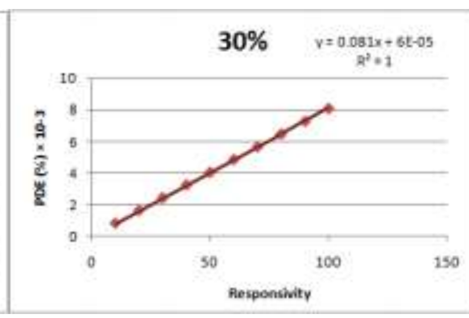
Table 2. Simulated PDE with virtual digital SiPM calculator.

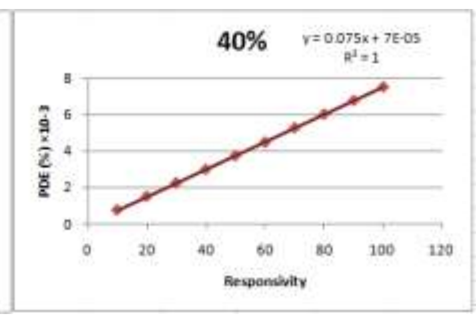
| **Responsivity (%)** | | **Over-voltage (% volts)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **20% ($\times 10^{-3}$)** | **30% ($\times 10^{-3}$)** | **40% ($\times 10^{-3}$)** | **50% ($\times 10^{-3}$)** | **60% ($\times 10^{-3}$)** | **70% ($\times 10^{-3}$)** | **80% ($\times 10^{-3}$)** | **90% ($\times 10^{-3}$)** | **100% ($\times 10^{-3}$)** |
| 10 | **PDE (%)** | 0.8782 | 0.8106 | 0.7527 | 0.7026 | 0.6586 | 0.6199 | 0.5855 | 0.5547 | **0.5269** |
| 20 | | 1.7564 | 1.6213 | 1.5055 | 1.4050 | 1.3173 | 1.2398 | 1.1171 | 1.1093 | 1.0538 |
| 30 | | 2.6346 | 2.4320 | 2.2582 | 2.1077 | 1.9760 | 1.8597 | 1.7564 | 1.6640 | 1.1581 |
| 40 | | 3.5130 | 3.2426 | 3.0110 | 2.8100 | 2.6346 | 2.4796 | 2.3420 | 2.2186 | 2.1077 |
| 50 | | 4.3910 | 4.0530 | 3.7640 | 3.5130 | 3.2930 | 3.0995 | 2.9273 | 2.7730 | 2.6346 |
| 60 | | 5.2690 | 4.8640 | 4.5165 | 4.2150 | 3.9520 | 3.7194 | 3.5130 | 3.3280 | 3.1615 |
| 70 | | 6.1470 | 5.6750 | 5.2690 | 4.9180 | 4.6110 | 4.3390 | 4.0980 | 3.8826 | 3.6884 |
| 80 | | 7.0260 | 6.4850 | 6.0220 | 5.6200 | 5.2690 | 4.9590 | 4.6840 | 4.4370 | 4.2150 |
| 90 | | 7.9040 | 7.2960 | 6.7750 | 6.3230 | 5.9280 | 5.5790 | 5.2690 | 4.9920 | 4.7420 |
| 100 | | **8.7820** | 8.1060 | 7.5270 | 7.0260 | 6.5860 | 6.1990 | 5.8550 | 5.5470 | 5.2690 |

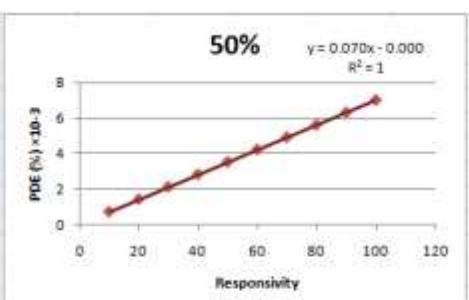
Table 3. Formulated models of PDE with varied over-voltage points under standard conditions.

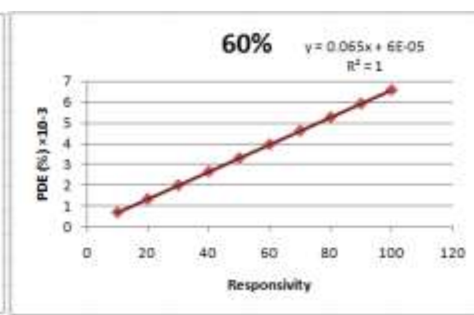
| Over voltage (%) | PDE Model equation with SiPM | Regression coefficient |
|---|---|---|
| 20 | PDE (%)= $\frac{(0.087R-3\times10^{-5})}{10^{-3}}$ | 1 |
| 30 | PDE (%)= $\frac{(0.081R-6\times10^{-5})}{10^{-3}}$ | 1 |
| 40 | PDE (%)= $\frac{(0.075R-7\times10^{-5})}{10^{-3}}$ | 1 |
| 50 | PDE (%)= $\frac{(0.070R)}{10^{-3}}$ | 1 |
| 60 | PDE (%)= $\frac{(0.065R-6\times10^{-5})}{10^{-3}}$ | 1 |
| 70 | PDE (%)= $\frac{(0.062R-3\times10^{-5})}{10^{-3}}$ | 1 |
| 80 | PDE (%)= $\frac{(0.058R+0.018)}{10^{-3}}$ | 0.9990 |
| 90 | PDE (%)= $\frac{(0.554R-1\times10^{-4})}{10^{-3}}$ | 1 |
| 100 | PDE (%)= $\frac{(0.054R-0.112)}{10^{-3}}$ | 0.9930 |

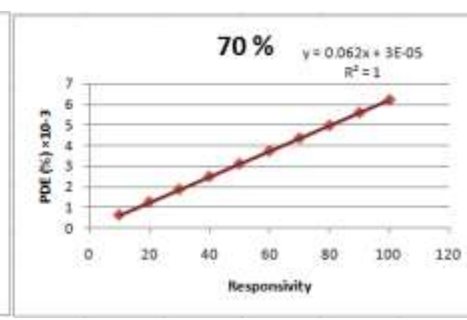


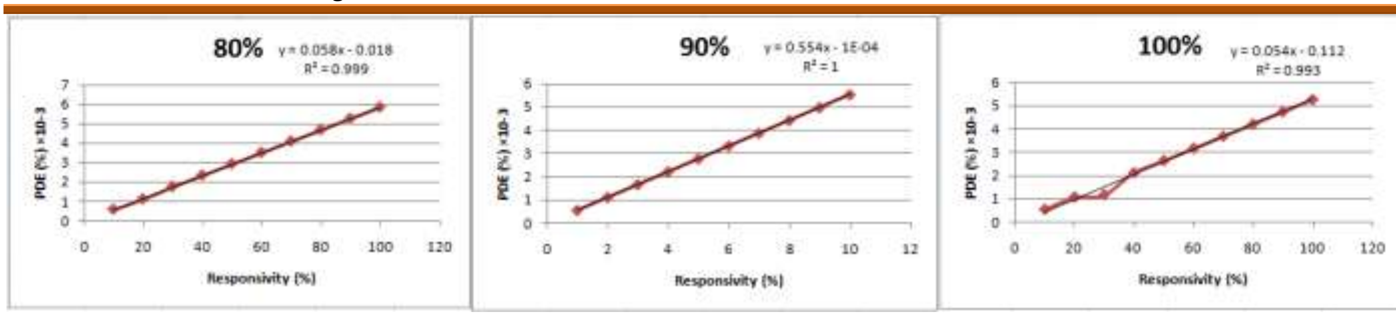



Figure 7. The plots of PDE (%) with the responsivity of SiPM at various overvoltages.

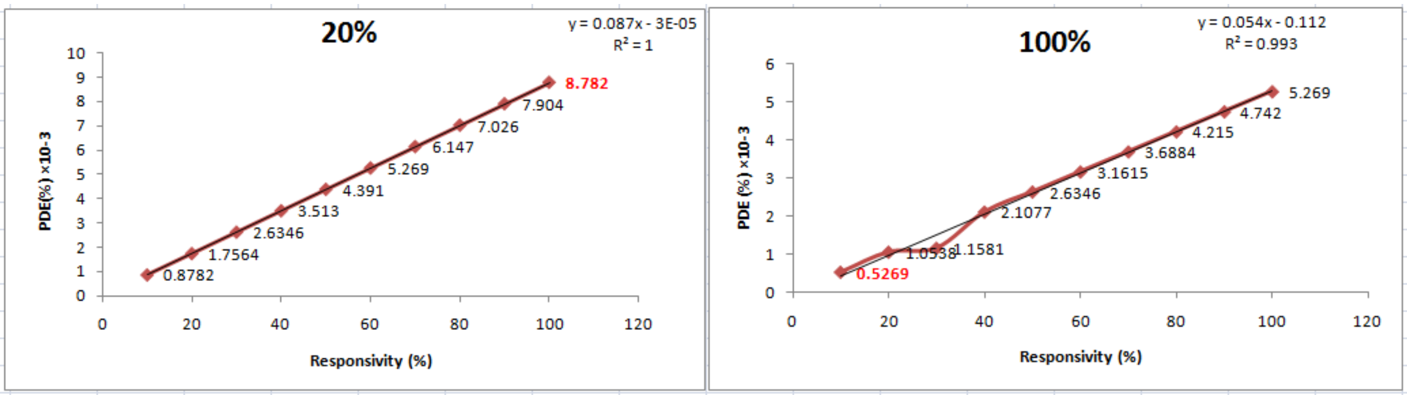



Figure 5. Linear model plots of PDEs (%) against the SiPM responsivities (%) at the respective value of the overvoltage.

The PDE calculator approach tends to simulate the operational algorithm of silicon photomultiplier at the after pulse maximum probability of 30%, multiplication gain of $10^6$, the maximum wavelength of light at 905nm with the variations of over-voltage activity and the responsivity of SiPM detector (Table 1). The impacts of the interactions of the percent over-voltage with the SiPM responsiveness were clearly expressed in table 2. Evidently, the maximum PDE was identified to be (8.7820 X 10-3)% at 20% over-voltage (80% net voltage) and 100% SiPM responsivity, while the minimum is (5.2690 X 10-4)% at 100% over-voltage(0% net voltage) and 10% responsivity (Table 2 and figure 5). Additionally, the respective PDE with the established over-voltages were factored in mathematical modeling as shown in table 3. These further affirmed the acceptance of PDE at the selected maximum and minimum values under the identified conditions.

## 4.0 CONCLUSION

Completely advanced varieties of silicon photomultipliers have been designed and developed. Their actual electro-physical characteristics have been deduced with the mode of their activities. However, further advancement is conceivable with the single-photon examination by improving the induction conditions that will favour higher photon detection efficiency. In view of the outcomes acquired so far, this innovation can practically displace older models of vacuum photomultiplier tubes in numerous applications, particularly where precise time factor, significantly low light levels, minimum consumption of power, size and attractive magnetic fields are the difficulties.

Hence, understanding the detection capacity of SiPM based on some conditions and parameters will practically define better insights into the advancement, applications and modifications in the nearest future especially in the areas of clinical imaging, security, optic communication system, physical science, and military applications. It is by and large apparent that the not so distant eventual fate of silicon photomultiplier improvement is to make a totally advanced quantum identifier with executable readout gadgets on a similar substrate. Such innovation will be a progression to a new level of quantum identification with opportunities for new applications.

## 5.0 REFERENCES

1. Stefan Gundacker and Arjan Heering (2020). TOPICAL REVIEW. The silicon photomultiplier: fundamentals and applications of a modern solid-state photon detector. Phys. Med. Biol. **65** 17TR01.

2. Marteau, J et al (2012). Readout architecture based on the use of Silicon Photomultipliers (SiPM, or MMPC). https://ui.adsabs.harvard.edu/abs/2012EGUGA..14.3069M/abstract

3. Fabio Acerbi and Stefan Gundacker (2019).Understanding and simulating SiPMs, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 926, 2019, Pages 16-35, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2018.11.118.

4. Fabio Acerbi et al (2015). NUV Silicon Photomultipliers with High Detection Efficiency and Reduced Delayed Correlated-Noise. IEEE Transactions on Nuclear Science 62(3):1-8.10.1109/TNS.2015.2424676

5. Fabio Acerbi et al (2015). Analysis of single-photon time resolution of FBK silicon photomultipliers. Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment 787:34-37 10.1016//j.nima.2014.10.057

6. A. N. otte et al (2004). New results from a test of silicon photomultiplier as readout for PET. Conference: Nuclear Science Symposium Conference Record, 2004 IEEE Volume: 6. 10.1109/NSSMIC.2004.1466693

7. A.N. Otte et al (2006). A measurement of the photon detection efficiency of silicon photomultipliers. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 567, Issue 1, 2006, Pages 360-363, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2006.05.145.

8. Valeri Saveliev (2010). Silicon Photomultiplier - New Era of Photon Detection. Source: Advances in Optical and Photonic Devices.https://www.academia.edu/25262709/Silicon_Photomultiplier_New_Era_of_Photon_Detection

9. York Haemisch et al (2012). Fully Digital Arrays of Silicon Photomultipliers (dSiPM) – a Scalable Alternative to Vacuum Photomultiplier Tubes (PMT).Physics Procedia, Volume 37, 2012, Pages 1546-1560, ISSN 1875-3892, https://doi.org/10.1016/j.phpro.2012.03.749.

10. Nurul A.C. Lah et al (2018). Engineered Nanomaterial in Electronics and Electrical Industries, In Micro and Nano Technologies. Handbook of Nanomaterials for Industrial Applications, Elsevier. 2018, Pages 324-364, ISBN 9780128133514.https://doi.org/10.1016/B978-0-12-813351-4.00021-3.

11. Huang et al (2018). Sipm integrated read-out: https://www.science.gov/topicpages/s/sipm+integrated+read-out.html

12. P. Buzhan et al (2003).Silicon photomultiplier and its possible applications. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. Volume 504, Issues 1–3, 2003, Pages 48-52, ISSN 0168-9002.https://doi.org/10.1016/S0168-9002 (03)00749-6.

13. Federico Capasso (1985). Physics of Avalanche Photodiodes .Semiconductors and Semimetals, Elsevier, Volume 22, Part D, 1985, Pages 1-172, ISSN 0080-8784, ISBN 9780127521534, https://doi.org/10.1016/S0080-8784 (08)62952-X.

14. UMHT, E. (2021). (Biomedical engineering) introduction to medical electronics applications [Arnold 1995](234s). https://issuu.com/elekromedikumht/docs/_biomedical_engineering__introducti

15. Centronic (2021). Silicon Photodiode Theory .http://userweb.eng.gla.ac.uk/william.ward/Optoelctronics%20suite%20info/3-1-6%20photodiode%20theory.pdf

16. Alexander Gottwald and Frank Scholze (2018). Advanced silicon radiation detectors in the vacuum ultraviolet and the extreme ultraviolet spectral range. Electronic and Optical Materials, Smart Sensors and MEMs (Second Edition), wood head publishing, 2018, Pages 151-170, ISBN 9780081020555, https://doi.org/10.1016/B978-0-08-102055-5.00007-3.

17. Mohammad Saleh et al (2002). Breakdown voltage in thin III–V avalanche photodiodes. Applied Physics Letters 79(24):4037 – 4039.10.1063/1.1425463

18. Thomas Frach et al (2009). The Digital Silicon Photomultiplier - Principle of Operation and Intrinsic Detector Performance. IEEE Nuclear Science Symposium conference record. Nuclear Science Symposium 10.1109/NSSMIC.2009.5402143

19. Lu Sun et al (2020). Sub wavelength structured silicon waveguides and photonic devices. Nanophotonics 9(6) 10.1515/nanoph-2020-0070

20. Jeff Hecht (2018). Lidar for Self-Driving Cars. Optics and Photonics News 29(1):26-35 10.1364/OPN.29.1.000026

21. Sara Ryding, B. (2021). How are Photomultiplier Tubes Used in Flow Cytometry?https://www.news-medical.net/life-sciences/How-are-Photomultiplier-Tubes-Used-in-Flow-Cytometry.aspx

22. Emilie Roncali and Simon R Cherry (2011). Application of Silicon Photomultipliers to Positron

Emission Tomography. Annals of Biomedical Engineering 39(4):1358-77.10.1007/s10439-011-0266-9

23. Slawomir Piatek (2018). Silicon photomultipliers: Operation, performance, and possible applications. https://hub.hamamatsu.com/us/en/webinar/sipm-operation-performance/index.html